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Infantile Nystagmus Syndrome Is Associated With Inefficiency of Goal-Directed Hand Movements

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PURPOSE. The effect of infantile nystagmus syndrome (INS) on the efficiency of goal-directed hand movements was examined.

METHODS. We recruited 37 children with INS and 65 control subjects with normal vision, aged 4 to 8 years. Participants performed horizontally-oriented, goal-directed cylinder displacements as if they displaced a low-vision aid. The first 10 movements of 20 back-and-forth displacements in a trial were performed between two visually presented target areas, and the second 10 between remembered target locations (not visible). Motor performance was examined in terms of movement time, endpoint accuracy, and a harmonicity index reflecting energetic efficiency.

RESULTS. Compared to the control group, the children with INS performed the cylinder displacements more slowly (using more time), less accurately (specifically in small-amplitude movements), and with less harmonic acceleration profiles. Their poor visual acuity proved to correlate with slower and less accurate movements, but did not correlate with harmonicity. When moving between remembered target locations, the performance of children with INS was less accurate than that of the children with normal vision. In both groups, movement speed and harmonicity increased with age to a similar extent.

CONCLUSIONS. Collectively, the findings suggest that, in addition to the visuospatial homing-in problems associated with the syndrome, INS is associated with inefficiency of goal-directed hand movements. (<http://www.trialregister.nl> number, NTR2380.)

Keywords: infantile nystagmus syndrome, children, sensorimotor development, goal-directed hand movements

To be able to participate properly in daily school activities, visually impaired children, like all children, need well-developed motor skills that allow them to handle devices, such as low-vision aids,¹ smartphones, pencils, and laptops. In young visually impaired children who are not yet using a visual aid, the visual feedback of their movements is structurally different from their normally sighted peers: fine details are not seen and, therefore, their interaction with surrounding objects has not the same stimulating effect. When visual acuity is low, motor development can be influenced or even delayed.^{2–9} Earlier studies have shown that fine and gross motor skills as well as control of balance are underdeveloped in children with a visual impairment.^{2–9} Furthermore, children with mild-to-severe visual acuity loss and amblyopia are known to generate grasping movements of lower quality than children with normal sight.^{10,11} Reimer et al.,¹² who studied the effect of visual impairment on goal-directed aiming in a small group of children with albinism, demonstrated that 8-year-old children with albinism were less accurate than the control group. In present-day society, in which the use of technical devices has increased dramatically, children indeed strongly rely on fine motor skills. In that context, it is useful to investigate the motor

skills of visually impaired children. A precise description of the effects of visual impairment on the efficiency of goal-directed hand movements still is lacking.

In the present study, we investigated goal-directed hand movements of children with infantile nystagmus syndrome (INS). This syndrome is the third cause of low vision in the Netherlands,¹³ and is characterized by involuntary oscillations of the eyes that typically are conjugate and horizontal in direction, and by infantile onset.^{14,15} As a direct result of the inability to maintain stable foveal vision, INS is associated with reduced visual acuity.^{16,17} The INS occurs in an isolated (idiopathic) form, or is accompanied by congenital or acquired defects in the visual system, such as albinism, bilateral optic nerve hypoplasia, infantile cataract, aniridia, or various inherited types of retinal degeneration.^{15,18–20} If INS is accompanied by another sensory disorder, a patient has two disorders (e.g., albinism and INS).¹⁹ Idiopathic and accompanied INS forms are included in this study, which makes the study group a realistic reflection of the prevalence of INS children in the Netherlands. The INS population is a very heterogeneous group. Evidence for a relation between stereopsis and fine motor skills in children with amblyopia (mean

age, 8.2 years) has been found.²¹ However, no clear relations have been described between stereopsis and motion in children with INS; therefore, we performed additional analyses regarding stereopsis.

The aim of the study was to examine the effects of visual impairment on the development of the efficiency of goal-directed hand movements in children with INS. Seemingly simple goal-directed movements, such as reaching, grasping, and manipulating objects, involve complex interactions between perceptual and motor systems. The primary modalities used for goal-directed movements include visual, proprioceptive, and vestibular subsystems. From a perception-action perspective, motor control emerges from the ongoing interaction between the performer and environment^{22–27} on the basis of associations between perception and action subsystems that already are established in newborns.^{27,28} With development, the different action and perception subsystems become more integrated, which results in more effective and adaptive motor behavior.

We used a Fitts aiming task²⁹ that was tailored to the skill of manipulating low-vision aids.³⁰ Originally, Fitts tasks required participants to perform fast and accurate back-and-forth movements of the finger tip or a pointing stylus between two predefined target areas. The speed and accuracy of such aiming movements rely critically on intact processing of visual and proprioceptive information, and on the movement amplitude and imposed target width as complexity factors.^{31,32} In the present study, the degree to which performance depended on vision was tested by manipulating target visibility, which was present in the first 10 movements and absent in the second 10 movements, and target distance (either 10 or 20 cm) as within-subject variables and scrutinizing the effects of these variables on movement time, endpoint accuracy, and harmonicity. Conceptually, the harmonicity index provides a means to determine the efficiency of sensorimotor control,^{33,34} which will be elaborated on in the Methods section. A more harmonic motion corresponds to a more (energetically) efficient motor performance. This approach is quite novel for the field of visual impairment research, although it has been applied successfully elsewhere.^{33–35}

We reasoned that group differences regarding the speed-accuracy effects of target visibility and target distance variations, potentially interacting with age, would provide insights into the sensorimotor control deficiencies in children with INS. Similar effects for the harmonicity index would point at additional structural motor-control efficiency limitations due to a poorly integrated perception-action system. Based on this rationale and the earlier research described above, two hypotheses were formulated. First, we hypothesized that children with INS would perform less accurate, slower, and less harmonic goal-directed movements than children with normal vision. Second, we hypothesized that the performance improvement as a function of age would be similar in children with INS and the control group, demonstrating that the expected age-independent motor performance differences were due to inefficient perception-action couplings rather than to a structural visual impairment that, in children with INS, might differentially hamper their aiming performance.^{36,37}

METHODS

Participants

Participants were 37 children with INS from client databases of all Dutch vision rehabilitation centers (mean age = 81 months; mean visual acuity = 0.2; 26 boys, 11 girls) and 65 control children with normal vision from regular primary schools in

the Netherlands (mean age = 79 months; mean visual acuity = 1.1; 26 boys, 39 girls). Children were included if they had no intellectual and/or motor impairments, normal birth weight (≥ 3000 grams), and birth at term (≥ 36 weeks of gestation). Nystagmus diagnoses were made after ophthalmological investigation. All children with INS had visual acuities ≤ 0.4 and ≥ 0.05 (E-chart, 6 m) in the better eye. Children with normal vision had visual acuities ≥ 0.8 . The study was approved by an accredited Medical Review Ethics Committee (CMO-Arnhem Nijmegen), and all protocols adhered to the guidelines of the Declaration of Helsinki. Informed consent was obtained from the participants' parents after explanation of the nature of the study.

Ophthalmological Examination

The clinical details of the children with INS are shown in Table 1. Distance visual acuity was measured monocularly and binocularly with correction with the Landolt C-test³⁸ at 5 m and the Illiterate E-chart³⁹ at 6 m under controlled lighting conditions in an ophthalmological setting. Near-visual acuity was determined binocularly with the angular LH version of the C-test⁴⁰ at 40 cm. Stereopsis was assessed with the Titmus Fly Test,⁴¹ and, if possible, with the TNO-test⁴² (a red-green system). Data regarding stereopsis scores of two normally sighted children are missing. Orthoptic examination was performed by orthoptists: they performed alternate cover test, cover-uncover test and, if necessary, the 4 diopter (D) base out prism test. A gross estimation of the visual field was obtained by confrontational techniques, to secure full view at the digitizer tablet. After cycloplegia, slit-lamp examination, and funduscopy and objective refraction were obtained, and, if necessary, the spectacle correction was prescribed or changed before the experiment started. All children with glasses wore them during the entire experiment.

Apparatus and Procedure

The participants were asked to perform goal-directed hand movements by displacing a cylinder-shaped object by means of a horizontal sliding movement across the surface of a digitizer tablet (type 21ux; Wacom, Saitama, Japan). The digitizer was positioned in front of the child's body midline and displayed two circles (diameter 25 mm) that acted as the start and end location of each movement. Children were asked to perform accurate and fast hand movements between the start and end target, as in a Fitts paradigm,²⁹ with both eyes open. The size of the cylinder matched that of a 6 D stand magnifier (diameter 56 mm, height 49 mm). An electronic sensor was placed in the center of the cylinder, allowing its X and Y positions to be digitally recorded at a sampling rate of 144 Hz. Children performed movements across two distances of either 10 or 20 cm horizontal distance between the center of the start and end target. Each participant received a random sequence of experimental conditions, each condition containing 20 movements. In the first 10 movements, target locations were visually presented, but in the second 10 movements they were not. Before the start of each trial, the child was asked to position the object in the starting circle on the digitizer, after which the experiment was started. A period of approximately 0.5 seconds later, the go signal was given and the target circle appeared on the digitizer. This was the indication for the child to slide the cylinder as fast and as accurately as possible toward the target location. When the target was reached, the former starting circle disappeared. The child had to wait for a random period of approximately 0.5 to 1.5 seconds before the next go signal was given and the target circle appeared (at the location of the former starting circle). The child then moved the object back

to that target circle. Ten movements back-and-forth were performed this way with visible targets. Next, 10 movements were generated to invisible targets, which meant that the children had to move the object to the formerly visible, but now remembered locations. General information about posture and performance was collected by video recordings. The video camera was positioned in front of the child and captured the digitizer tablet and the upper body of the child, including the hand moving the cylinder.

Data Analysis

Cylinder-position data were filtered using a dual-pass, low-pass Butterworth filter with a cut-off frequency of 6 Hz⁴³ and subsequently segmented into separate movements. The start and end of the movement were found by means of a semiautomatic search procedure starting from the middle of each trajectory and finding the samples at which the object velocity exceeded a threshold of 10 mm/s. Figures 1A and 1B show 10 movements from starting point to endpoint for a control subject and a representative child with INS, respectively. For each movement, the movement time (MT) was determined in seconds. A lower MT indicates a higher average speed and, thus, a faster performance.

For the 10 movements that were repeated within each condition, an endpoint variability (EV) measure reflecting spatial accuracy was calculated. The EV is a frequently used measure of accuracy in goal-directed aiming tasks^{44–46} and captures the adaptability of error-correction mechanisms.⁴⁷ The EV was calculated by determining the scatter of the endpoint locations of all movements for each condition (Fig. 2). For each trial, the endpoint scatter (variable error) was used to determine the 95% endpoint ellipses.⁴⁸ First, we determined the axis of the principle direction. Second, we computed the major and minor axes (perpendicular) of the endpoint scatter. Third, we calculated the size of the 95% endpoint ellipse: $\text{area} = \pi \cdot A \cdot B$, where A and B represented two standard deviations ($1.96 \cdot \text{SE}$) of the length of the major and minor axes, respectively. The EV is the surface of the area (95% endpoint ellipse) in cm^2 . A lower score on EV indicates a more accurate performance.

The acceleration versus displacement graphs, that are called Hooke's portraits (Figs. 1C, 1D), are used for the assessment of the harmonicity of the movement.^{33–35,49} To this end, we applied the statistical method of linear regression, to fit a straight line onto each Hooke's portrait. Conceptually, the harmonicity of cyclical movements offers a description of the efficiency with which kinetic energy is being recycled during back-and-forth movements. In cyclical movements relatively modicum energy is lost toward the end of the movement, resulting in Hooke's portraits that approach linear graphs.^{33–35,49} For discrete movements, harmonicity indices reflect the efficiency with which potential energy that is built up during acceleration is being dissipated during deceleration and coming to a standstill. Hooke's portraits of discrete movements (and highly precision-constrained cyclical movements) are described by their "asymmetric N-shape" in the literature.⁴⁹ The arc-like endings at each side of these Hooke's portraits represent the sudden (nonharmonic) acceleration and deceleration phases of the strokes, respectively, which are associated with the fast generation and dissipation of energy.^{34,49,50} Figure 1 displays samples of Hooke's portraits of the 10 strokes made by one representative control child (Fig. 1C) and 10 single strokes made by one representative child with INS (Fig. 1D) in the 10-cm amplitude condition. Both portraits show relative nonharmonic movements, displayed by the asymmetric N-shape.³⁴ Next, a linear regression line was fitted through all the points constituting the Hooke's portrait

(i.e., through the entire curve), for each individual stroke (Figs. 1C, 1D). The R Square (RSq) value is an index ranging from 0 to 1, quantifying how well the curve approximates this straight line. (An alternative kinematic measure reflecting movement efficiency is called index of harmonicity [H] and is used to express harmonicity of acceleration portraits.^{22,23} The H value is calculated over a segment of a stroke from one movement midpoint to the next movement midpoint. In our study design, it is not possible to calculate H, because our design includes discrete movements. Therefore, we can only analyze movement segments from one target to the next target instead of from one movement midpoint to the next movement midpoint. Therefore, an alternative measure for the harmonicity is used: the RSq of the linear fit of the acceleration profile.) The arc-like endings at each side of a Hooke's portrait, which are larger in nonharmonic movements, reduce the statistical fit of the regression line, resulting in lower RSq. In this sense, RSq is a measure of the linearity of the Hooke's portrait, and is directly related to the harmonicity of the movement. A higher RSq (i.e., closer to 1), associated with a more linear Hooke's portrait, indicates a simple harmonic motion, corresponding to a more (kinetically) efficient motor performance.

For the three dependent variables (MT, EV, and RSq), the data were averaged across the 10 repetitions of each task condition and entered into SPSS (SPSS, Inc., Chicago, IL, USA). General linear model procedures were carried out, with INS group as between-subjects factor, age (in months) as covariate, and target visibility as within-subject factor, for the 10 and 20 cm condition, separately. Only 2-way interaction effects including group (INS versus control group) and target visibility (visible and invisible) are reported, in accordance with our research hypotheses. Preliminary analyses revealed no significant difference regarding stereopsis and performance scores between children with INS and albinism and children with INS without albinism, and were reason to leave albinism out of the General Linear Model procedures. To investigate the effect of visual impairment on the performance of children with INS, Pearson correlations were calculated between their visual acuity scores and mean performance scores (MT, EV, RSq). If correlations were significant, step-down correlation analyses were conducted for the different conditions. Floor and ceiling effects resulted in not normally distributed stereopsis scores. Consequently children were clustered according to their stereopsis level; "nil" if "no" stereoscopic response could be measured, "reduced" if response indicated stereopsis between 800 and 60 sec arc, and "normal" if response indicated stereopsis better than or equal to 40 sec arc.²¹ The χ^2 analyses were performed to compare the level of stereopsis between children with INS and children with normal sight. We performed *t*-tests to compare performance scores (MT, EV, RSq) of the subgroup with INS and reduced stereopsis with performance scores of the subgroup with INS and no stereopsis. To test the second hypothesis, first, Pearson correlations between age and visual acuity were calculated, because in typically developing children and children with INS, visual acuity increases with age.³⁷ Second, Pearson correlations were calculated between MT, EV, RSq, and age (in months) controlling for visual acuity, per vision group, and target visibility condition, separately for movements with an amplitude of 10 and 20 cm.

RESULTS

Figure 3 shows the mean MT, EV, and RSq for each group (normally sighted versus INS) as a function of target visibility (visible versus invisible) and amplitude (10 and 20 cm).

TABLE 1. Clinical Characteristics of Children With INS

Child	Age, y	DVA			NVA		Diagnosis	Deviation	Stereopsis, sec arc	Refractive Correction
		ODS*	OD†	OS†	Ang‡	ODS				
1	4	0.2	0.2	0.16	0.2		Idiopathic INS	L esotropia	Nil	No correction
2	4	0.12	0.08	0.08	0.08		Albinism, INS	Orthophoria	Nil	R S: +3.50 C: -2.75 A: 180° L S: +5.00 C: -2.00 A: 176°
3	4	0.06	0.04	0.1	0.125		Albinism, INS	R exotropia	100	R S: +6.00 C: -2.50 A: 3° L S: +3.75 C: -2.50 A: 172°
4	4	0.08	0.1	0.08	0.08		Albinism, INS	R exotropia	Nil	R S: +4.25 C: -2.00 A: 14° L S: +4.75 C: -2.00 A: 170°
5	4	0.1	0.06	0.06	0.08		Achromatopsia, INS	Orthophoria	Nil	R S: +3.25 C: -3.75 A: 178° L S: +2.75 C: -2.50 A: 179°
6	5	0.06	0.06	0.05	0.08		Achromatopsia, INS	Orthophoria	Nil	R S: +4.50 C: -1.00 A: 3° L S: +4.00 C: -1.00 A: 15°
7	5	0.24	0.2	0.2	0.25		Retinoschisis (X linked), INS	Orthophoria	480	No correction
8	5	0.2	0.2	0.2	0.16		Albinism, INS	Orthophoria	400	R S: - 0.25 C: -1.00 A: 69° L S: plan C: -1.75 A: 100°
9	5	0.12	0.2	0.16	0.25		Albinism, INS	L esotropia	800	R S: plan C: -1.75 A: 15° L S: plan C: -1.00 A: 55°
10	5	0.2	0.16	0.2	0.3		Albinism, INS	Orthophoria	Nil	R S: +1.00 C: -2.00 A: 1° L S: +2.50 C: - 2.25 A: 172°
11	5	0.24	0.2	0.25	0.2		Idiopathic INS	Orthophoria	nil	R S: +3.25 C: -1.25 A: 10° L S: +2.50 C: -2.25 A: 172°
12	5	0.2	0.16	0.2	0.32		Idiopathic INS	Orthophoria	100	R S: +2.50 C: -0.75 A: 169° L S: +3.00 C: -1.75 A: 7°
13	6	0.36	0.7	0.6	0.63		Hypermetropia (>4D), INS	Orthophoria	100	R S: +4.50 C: -1.75 A: 170° L S: +5.00 C: -2.00 A: 11°
14	6	0.08	0.125	0.16	0.16		Albinism, INS	R esotropia	Nil	No correction
15	6	0.12	0.1	0.1	0.1		Albinism, INS	orthophoria	800	R S: +4.75 C: -2.5 A: 7° L S: +4.5 C: -3.75 A: 180°
16	6	0.36	0.2	0.25	0.32		Albinism, myopia >6D, INS	R Exotropia	100	R S: - 5.50 C: -1.25 A: 159° L S: -3.50 C: -0.75 A: 180°
17	6	0.18	0.16	0.16	0.16		Myopia (high >6 D), INS	Orthophoria	Nil	R S: -9.00 C: -1.00 A: 180° L S: -8.00 C: -1.00 A: 180°
18	6	0.36	0.3	0.4	0.5		Idiopathic INS	L esotropia	400	R S: +4.75 C: -0.50 A: 170° L S: +3.50 C: -0.50 A: 180°
19	6	0.12	0.2	0.125	0.32		Congenital cataract (aphakia), INS	Orthophoria	Nil	R S: +16.25 C: -2.00 A: 152° L S: +17.00 C: -1.50 A: 5°
20	6	0.24	0.25	0.32	0.32		Idiopathic INS	Orthophoria	200	R S: -1.25 C: plan A: 180° L S: - 1.25 C: plan A: 180°
21	6	0.12	0.25	0.32	0.32		Idiopathic INS	Orthophoria	400	No correction
22	7	0.12	0.2	0.2	0.25		Albinism, INS	Orthophoria	240	R S: +0.75 C: -5.00 A: 167° L S: +0.75 C: -4.5 A: 5°
23	7	0.24	0.2	0.25	0.32		Idiopathic INS	Orthophoria	Nil	R S: -2.25 C: -0.75 A: 130° L S: -1.75 C: -0.25 A: 7°
24	7	0.36	0.25	0.25	0.32		Albinism, INS	R esotropia	Nil	R S: +2.25 C: -1.25 A: 8° L S: +0.75 C: -0.75 A: 110°
25	7	0.36	0.32	0.1	0.25		Idiopathic INS	L estotropia	Nil	R S: +4.25 C: -3.00 A: 5° L S: +4.50 C: -3.25 A: 163°
26	7	0.2	0.12	0.2	0.2		Albinism, INS	Orthophoria	400	R S: +3.75 C: -2.50 A: 175° L S: +3.50 C: -1.75 A: 175°
27	8	0.18	0.25	0.16	0.25		Congenital cataract (aphakia), INS	L esotropia	Nil	R S: +12.00 C: -3.75 A: 14° L S: +18.50 C: -6.00 A: 52°
28	8	0.36	0.32	0.32	0.4		Idiopathic INS	Orthophoria	140	No correction
29	8	0.24	0.2	0.25	0.2		Albinism, INS	R esotropia	Nil	R S: +7.25 C: -4.25 A: 12° L S: +7.00 C: -3.75 A: 173°
30	8	0.24	0.16	0.32	0.32		Nightblindness (CSNB), INS	Orthophoria	Nil	R S: -10 C: -3.00 A: 104° L S: -10 C: -1.50 A: 111°
31	8	0.3	0.125	0.4	0.4		Nightblindness (CSNB), INS	R esotropia	Nil	R S: +3.75 C: plan A: 180° L S: +3.50 C: plan A: 180°
32	8	0.2	0.25	0.25	0.25		Albinism, INS	Orthophoria	100	R S: +4.50 C: -3.25 A: 10° L S: +3.50 C: -3.25 A: 165°
33	8	0.24	0.04	0.25	0.4		Retinoschisis (X linked), INS	R exotropia	480	R S: -0.50 C: -2.00 A: 4° L S: +1.75 C: -1.25 A: 150°

TABLE 1. Continued

Child	Age, y	DVA			NVA		Diagnosis	Deviation	Stereopsis, sec arc	Refractive Correction
		ODS*	OD†	OS†	Ang‡	ODS				
34	8	0.24	0.25	0.4	0.25		Albinism, INS	Orthophoria	800	R S: +5.25 C: −1.75 A: 21° L S: +5.25 C: −1.50 A: 15°
35	8	0.12	0.125	0.08	0.16		CSNB, INS	Orthophoria	800	R S: −4.50 C: −0.50 A: 159° L S: −5.25 C: −1.50 A: 167°
36	8	0.36	0.32	0.32	0.4		Idiopathic INS	Orthophoria	200	R S: +1.00 C: −2.50 A: 38° L S: +1.00 C: −2.75 A: 139°
37	8	0.4	0.2	0.2	0.32		Aniridia, INS	Orthophoria	400	R S: +4.75 C: −0.75 A: 31° L S: +5.50 C: −0.50 A: 151°

DVA, distance visual acuity; ODS, binocular; OD, right eye; OS, left eye; NVA, near visual acuity; ang, angular; CSNB, congenital stationary night blindness.

* Distance visual acuity binocularly at 6 m in decimals as measured with E-gratings.
† Distance visual acuity monocularly at 5 m in decimals as measured with C-test angular.
‡ Near visual acuity binocularly at 40 cm in decimals as measured with LH line version of the C-test.

Children With INS Versus Children With Normal Vision

A longer MT was found in the INS group in the 10 cm condition, $F(1, 99) = 13.59$, $P < 0.001$, and 20 cm condition, $F(1, 99) = 11.50$, $P = 0.001$, indicating slower hand

movements in children with INS than in children with normal vision (Fig. 3A). A larger EV was found in the INS group in the 10 cm condition, $F(1, 99) = 6.61$, $P = 0.012$, indicating a less accurate performance in children with INS than children with normal vision (Fig. 3). In the 20 cm condition, the group effect on EV approached statistical significance, $F(1, 99) =$

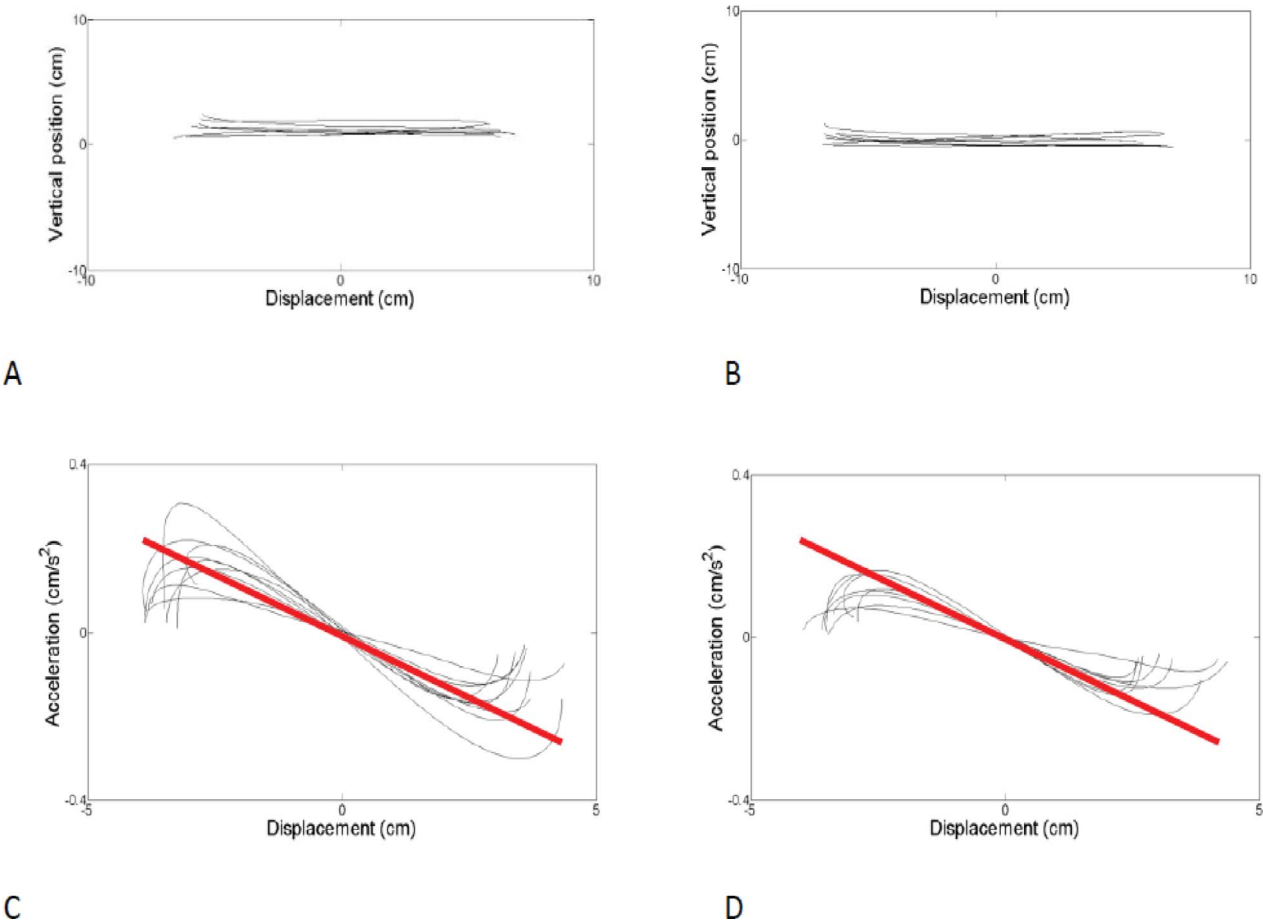


FIGURE 1. Depicts the 10 horizontal strokes produced in the 10-cm amplitude condition by a representative child with normal vision (A) and a child with INS (B), and Hooke's portraits (acceleration versus horizontal displacement graphs) produced by a representative child with normal vision (C) and a representative participant with INS (D). A linear regression line (red line) was fitted through all the points constituting the Hooke's portraits (in [C, D]). The RSq value is an index ranging from 0 to 1, quantifying how well the curve approximates this straight line (in [C], mean RSq is 0.67; in [D], mean RSq is 0.71). The arc-like endings at each side of a Hooke's portrait, which are larger in nonharmonic movements, reduce the fit of the regression line, resulting in lower RSq. This corresponds to a less (kinetically) efficient motor performance.

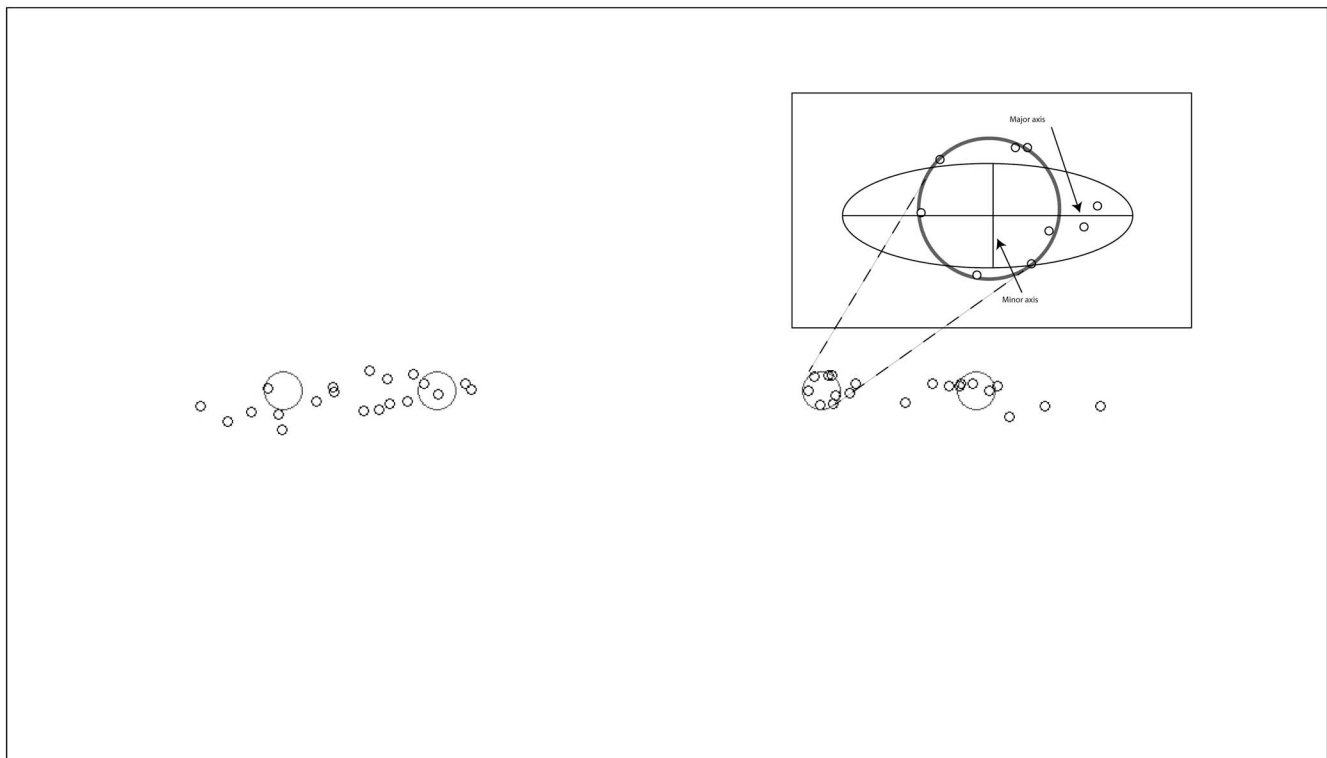


FIGURE 2. Endpoint distributions for movements to targets with two distances by one child. Endpoints for individual movements are represented by *small circles*. *Large circles* show target locations. The distributions of endpoints for movements to one target is fitted with a surrounding *ellipse*. Here, the length of the major and minor axes are scaled such that 95% of the population of end-points should fall within the boundaries of the ellipse. The EV is the surface of the 95% endpoint ellipse in cm^2 , calculated by $\text{area} = p \cdot A \cdot B$, where A and B represented 2 SDs ($1.96 \cdot \text{SE}$) of the length of the major and minor axes, respectively.

3.55, $P = 0.062$ (Fig. 3B). A larger RSq was found in the INS group in the 10 cm condition, $F(1, 99) = 9.90$, $P = 0.002$, and the 20 cm condition, $F(1, 99) = 11.44$, $P = 0.001$, indicating a less harmonic performance in children with INS than in children with normal vision (Fig. 3C).

In summary, the INS group made slower (10 and 20 cm condition), less accurate (10 cm condition), and less harmonic (10 and 20 cm condition) goal-directed hand movements than the normally sighted group.

Target Visibility

Target visibility had a main effect on MT in the INS and normally sighted group in the 10 cm condition, $F(1, 99) = 10.20$, $P = 0.002$, and 20 cm condition, $F(1, 99) = 15.97$, $P < 0.001$, indicating a slower performance in the invisible target condition (Fig. 3A). Target visibility had a main effect on EV in the INS and normally sighted group in the 10 cm condition, $F(1, 99) = 14.86$, $P < 0.001$, and 20 cm condition, $F(1, 99) =$

9.37, $P = 0.003$, indicating a less accurate performance in the invisible target condition (Fig. 3B). An interaction effect between target visibility and vision group in the 10 cm condition, $F(1, 99) = 6.66$, $P = 0.011$, indicates that target visibility affected the EV more in the INS group than in the normally sighted group. Target visibility had no significant main effect on RSq in the INS and normally sighted group in the 10 cm condition, $F(1, 99) = 3.67$, $P = 0.058$, and the 20 cm condition, $F(1, 99) = 2.44$, $P = 0.122$ (Fig. 3C).

In summary, INS and normally sighted children made slower and less accurate movements when moving toward previously visible target locations. Furthermore, target visibility affected the EV more in the INS group than in the normally sighted group in the 10 cm condition.

Visual Acuity

On average, the Pearson correlations between visual acuity and mean MT, visual acuity and mean EV, and visual acuity and

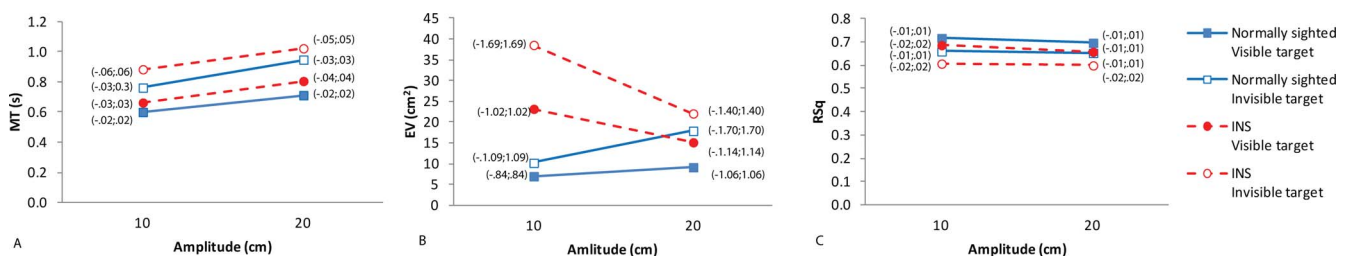


FIGURE 3. Mean MT in seconds (A), EV in cm^2 (B), and Hooke's portrait linearity (RSq, [C]) with target visible and target invisible for the normally sighted group and the INS group in the 10 and 20 cm conditions. The SE is specified between *parentheses*.

TABLE 2. The INS Group's Pearson's *r* and *P* Values Between Visual Acuity* and MT, Visual Acuity and EV, and Visual Acuity and RSQ

			MT		EV		RSq	
			<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>	<i>r</i>	<i>P</i>
Group	Conditions							
INS	10	Visible target	−0.45	0.005	−0.33	0.045	0.38	0.019
		Invisible target	−0.34	0.040	−0.33	0.049	0.25	0.136
	20	Visible target	−0.33	0.045	−0.25	0.136	0.19	0.249
		Invisible target	−0.24	0.156	−0.18	0.280	0.11	0.506
Normally Sighted	10	Visible target	−0.21	0.087	−0.23	0.069	0.21	0.087
		Invisible target	−0.13	0.298	−0.40	0.001	0.10	0.409
	20	Visible target	−0.38	0.002	−0.21	0.095	0.29	0.021
		Invisible target	−0.12	0.351	−0.34	0.006	0.06	0.634

MT, movement time; EV, endpoint variability; RSQ, Hooke's portrait linearity.
* Visual acuity at 6 m in decimals as measured with E-gratings.

mean RSq were Pearson's $r = -0.39$, $P = 0.030$, Pearson's $r = -0.38$, $P = 0.020$, and Pearson's $r = 0.21$, $P = 0.217$, respectively. The results clearly show that visual acuity correlates negatively with the speed and accuracy of the goal-directed hand movements as expected. Table 2 shows, for the INS and normally sighted groups for each condition, the Pearson correlations between visual acuity scores on the one hand and mean MT, EV, and RSq scores on the other.

Of the children with normal vision 84.1% had "normal stereopsis," 15.9% had "reduced stereopsis," and none had "no stereopsis." None of the children with INS had "normal stereopsis," 51.4% had "reduced stereopsis," and 48.6% had "no stereopsis." The variation in level of stereopsis was significant between the normally sighted and INS groups, $\chi^2_{(df=2)} = 71.89$; $P < 0.001$.

Performance of children with INS with reduced stereopsis was compared to the performance of children with INS and no stereopsis. In the 10 cm condition, we found no significant differences in performance speed, $t(35) = -0.64$, $P = 0.525$, accuracy, $t(35) = -0.139$, $P = 0.183$, and efficiency, $t(35) = -0.32$, $P = 0.749$. We found no significant differences in performance speed, $t(35) = -0.32$, $P = 0.750$, accuracy, $t(35) = -0.98$, $P = 0.334$, and efficiency, $t(35) = -0.09$, $P = 0.932$, in the 20 cm condition either.

In conclusion, normally sighted children had a significant better stereopsis than children with INS. In the INS group, no significant differences in performance were found between children with reduced stereopsis and no stereopsis.

Age Effects

Figure 4 shows MT, EV, and RSq plotted as a function of age with regression lines representing the linear relation between variables and age, in movements with an amplitude of 10 cm. The results for the 20 cm amplitude condition were comparable. While controlling for visual acuity, correlation analyses were conducted per vision group and target-visibility condition, in movements with an amplitude of 10 and 20 cm (Table 3). We controlled for visual acuity because, as expected, positive correlations between age (months) and visual acuity (decimals) were found in the INS and normally sighted group, Pearson's $r = 0.518$, $P = 0.001$, and Pearson's $r = 0.355$, $P = 0.004$, respectively.

In summary, as a function of age, the similar movement-efficiency changes were observed in the children with INS and in the control group.

DISCUSSION

Performance of Goal-Directed Hand Movements in Children With INS

With regard to the first hypothesis, we found that children with INS performed goal-directed hand movements more slowly, less accurately (particularly in small amplitude movements; i.e., 10 cm), and less harmonically than children with normal vision. This seems in contradiction with the study of Reimer et

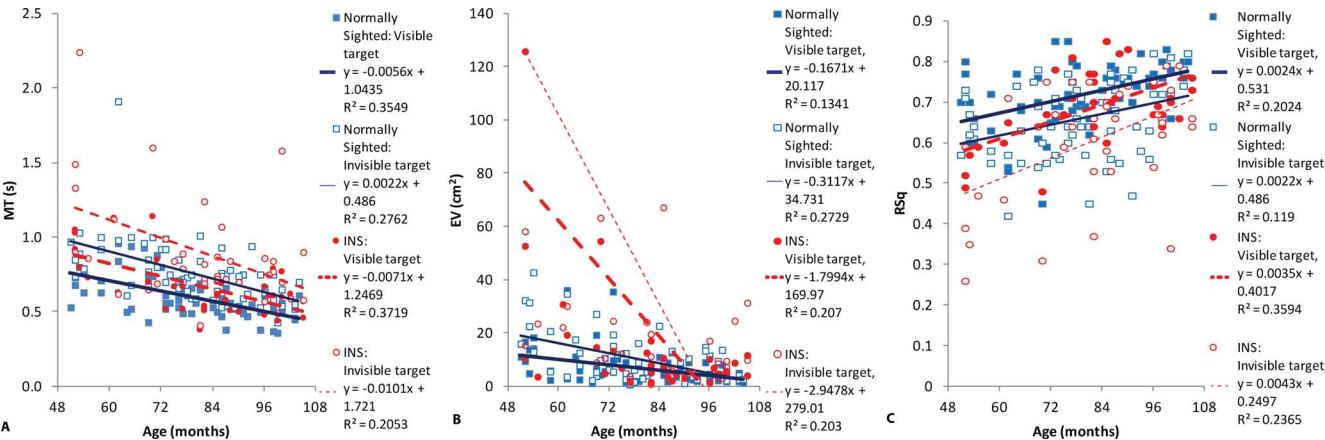


FIGURE 4. Mean MT in seconds (A), EV in cm² (B), and Hooke's portrait linearity (RSq, [C]) separately for vision group (normally sighted versus INS) and target visibility condition (visible versus not visible) plotted as a function of age, for movements with an amplitude of 10 cm. The regression lines represent the linear relation between MT, EV, and RSq on the one hand and age on the other. The legend shows regression equation (*r*), and corresponding *R*² values per vision group and target visibility condition.

TABLE 3. Pearson's *r* and *P* Values Between MT, EV, and RSq on the One Hand and Age in Months on the Other, for Children With Normal Vision and INS, in Movements With an Amplitude of 10 and 20 cm With Visible and Invisible Targets

Group	MT				EV				RSq			
	10		20		10		20		10		20	
	VT	IVT	VT	IVT	VT	IVT	VT	IVT	VT	IVT	VT	IVT
Normally sighted												
<i>r</i>	−0.57	−0.52	−0.61	−0.51	−0.31	−0.45	−0.35	−0.34	0.31	0.3	0.18	0.19
<i>P</i>	<0.001	<0.001	0.013	0.003	0.012	<0.001	0.005	0.005	0.012	0.022	0.357	0.129
INS												
<i>r</i>	−0.50	−0.35	−0.27	−0.51	−0.35	−0.35	−0.19	−0.52	0.51	0.44	0.21	0.39
<i>P</i>	0.002	0.039	0.109	0.002	0.036	0.037	0.270	0.764	0.002	0.008	0.210	0.019

VT, Visible target; IVT, Invisible target.

al.,¹² who investigated goal-directed aiming in visually impaired children with albinism. They reported a less accurate performance for the INS group compared to the normally sighted group, but found no significant differences between the two groups in speed. The population in that study, however, was older (eight years), smaller ($N = 11$), and included only children with albinism. One might argue that the slower movements for the INS group found in the present study resulted from longer movement trajectories as consequence of less accurate movements. We found evidence against this argument, because there were no significant differences in trajectory length between INS and normally sighted children. The origin of the slower and less accurate goal-directed movements in children with INS should, therefore, be found by slower or suboptimal sensorimotor processes, which were partly captured by our analyses of harmonicity and its variations as a function of visual acuity and target visibility.

Efficiency of Goal-Directed Hand Movements in Children With INS

The analysis of harmonicity provided additional insights in goal-directed aiming at the level of sensorimotor coordination. The Hooke's portraits of children with normal vision (Fig. 1C) as well as children with INS (Fig. 1D) revealed relatively nonharmonic movements, resembling those observed in adults performing under high precision constraints.³⁴ Moreover, children with INS demonstrated less harmonic movements than children with normal vision. To elaborate, in rhythmical aiming movements, under low-precision constraints a moving arm acts as a linear oscillator displaying simple harmonic motion. Kinetic energy built up during one movement is stored as potential (elastic) energy in the tendons and muscles, and released at the reversal point, that is, the start of the next movement. In this way, only little kinetic energy is lost.^{35,51} Under high-precision constraints, however, it is likely that high levels of cocontraction occur to arrive precisely and with low speed within the designated target area. Such conditions have a negative effect on the harmonicity of the movement and the dissipation of kinetic energy.⁵² One way to express the results regarding harmonicity in the present study is that children performing aiming movements in a Fitts task seem to experience a task difficulty that is "subjectively" higher than adults with the same set of task constraints. These less harmonic movements might be interpreted as reflecting less optimal sensorimotor coordination or cocontraction regulation in children than in adults, which is accompanied by more dissipation of energy in each stroke. For children with INS, the less harmonic movements reflect their suboptimal motor

efficiency, which is inferior compared to children with normal vision. In other words, the poorer goal-directed hand movements in the INS group may result from inefficient perception-action couplings or cocontraction strategies probably because the satisfaction of multiple constraints underlying task performance (i.e., fast as well as accurate aiming) is more difficult.³⁴

The Influence of Vision on Goal-Directed Hand Movements in Children With INS

The analysis of visual acuity and target visibility effects on the motor efficiency parameters under scrutiny provided additional insights into the direct and indirect influence of vision on goal-directed aiming. All children with INS were visually impaired with a visual acuity between 0.4 and 0.05. The degree of visual impairment in the INS group was related to movement speed and accuracy, especially in the condition with a lower level of difficulty (10 cm amplitude movements; see Table 2). A lower visual acuity was associated with a slower and less accurate performance. A poorer visual acuity provided less optimal feedback (even in the conditions with invisible targets, because children still had global information of the task setting and their arm) that probably directly affected the ability to guide the movement and homing-in to the target.¹² The degree of visual impairment was not related to harmonicity (except for the 10 cm condition with visible targets), which provided additional evidence that this is more a sensorimotor coordination problem rather than being only a visual perceptual problem.

To analyze the direct influence of vision on goal-directed aiming, target visibility was manipulated. As expected, invisible targets caused slower and less accurate movements in children with INS and in children with normal vision. With respect to the effect of target visibility, one might expect that the reduced visual information would make the INS children's movements rely more on the other sensory systems. However, performance of children with INS was even less accurate than that of the children with normal vision when targets were invisible, in the 10 cm condition. We interpret the poorer performance of children with INS in the invisible target condition from a perception-action perspective (see also the report of Schurink et al.¹). In this context motor control including goal-directed hand movements merges from the ongoing interaction between the child and the environment.²²⁻²⁷ Within this context, action control, like action development generally is approached as a dynamic system in which organismic, environmental and task constraints interact to establish optimal patterns of coordination. With development, the different action and perception subsystems become more

integrated, which results in more effective and adaptive motor behavior.⁵³ In light of this perspective, the relatively inefficient movements of the INS children compared to their normally sighted peers, points to a continuous problem in integrating action and perception. These problems remain or even exacerbate when visual information was reduced (invisible targets). We advocate that these motor control problems are a result from the inefficient perception-action integration earlier in life, suggesting a developmental problem. In conclusion, we interpret the poorer performance of children with INS not as caused by poorer vision directly, because the influence of vision was excluded in this condition, but as resulting from an inefficient coupling between perception and action.

This interaction effect for accuracy between group and target visibility was not duplicated in the 20 cm condition. Accordingly, the problems with the integration of perception and action seem task-specific. In arm movements with a larger amplitude, children with INS show less (extreme) problems compared to children with normal vision. According to Fitts' law,²⁹ with target width being kept constant, movements with an amplitude of 10 cm are relatively easier than movements with an amplitude of 20 cm, the Index of Difficulty being 3 and 4, respectively. So, INS children indeed experience a subjective task difficulty that is related not only to the task, but also to the inefficiency of their sensorimotor coordination.

Age-Specific Differences in Goal-Directed Hand Movements

Regarding the second hypothesis, as expected, in both groups movements of older children were more accurate, faster and more harmonic than that of younger children. In line with previous research,^{37,54} also visual acuity improved with age in children with INS and normal vision. One might hypothesize that improvement of goal-directed behavior results from a better visual acuity for the older children. We present two arguments against this hypothesis. First, in the correlation analyses, we controlled for visual acuity. Second, age effects in children with INS and normal vision also were present when influence of vision was excluded (invisible targets), so poorer performance in the INS group was not caused (solely) by poorer vision. Enhancement of goal-directed behavior in older INS children results probably from the improving integration of the action and perception subsystems, due to development and experience.

Although the problems in calibration and integration of perception-action subsystems in children with INS seem to be smaller in older children, under certain conditions these children still perform less accurately, slower and less harmonically than children with normal vision. So, in children with INS, inefficiency of sensorimotor control is not fully recovered at the age of eight years. This finding has important clinical implications. For rehabilitation purposes, it is important to instigate interventions at a young age.^{55,56} A properly developed efficiency of goal-directed hand movements is essential for handling objects (for instance a computer mouse or pen), visual aids, and other (fine) hand and arm activities.¹ This emphasizes the importance of these results for everyday life.

One of the possible causes of inefficiency of the perception-action system is that children with INS are less stimulated to interact with their environment, because it appears less visually detailed and alluring to them and, as a result, provides fewer (obvious) opportunities for action. For example, they do not easily detect small objects and details on surfaces in their environment and, therefore, are not challenged as much to interact with them, or in a less proficient way at least. This, in turn, leads to less detailed visual inspection, less object

manipulation, underpractice of fine-motor skills and so on; in other words, they experience a substantial lack of valuable sensory-motor experiences. As a result, in INS children, perception and action subsystems are, arguably, less integrated and attuned to each other, resulting in less differentiated, effective, and adaptive goal-directed behavior. The key contribution of the analyses presented here is that we should not treat this as a problem of poorer vision alone, but instead we should focus on the interaction between perception and action, for diagnostic purposes as well as in intervention.

In our study, visually impaired children with INS, including idiopathic INS ($N = 10$) and INS with associated visual deficit ($N = 27$), were investigated. A study weakness is that we could not analyze the direct effect of INS on goal-directed behavior, because we could not perform nystagmography. A quantification of nystagmus (amplitude and frequency) would have been necessary, as well as a separation of the idiopathic INS group from the group with INS with associated visual deficit group. Nystagmus waveforms can be changed by individuals' strategies⁵⁷ and visual demand.⁵⁸ So, ideally the role of nystagmus could be analyzed by eye-movement recordings during the task. However, eye-movement recording with a high sample frequency and with the possibility of free head movements is not yet available. The young age of the children, the experimental set up (with a horizontally positioned digitizer) and the load on the children during the whole experiment (including ophthalmologic assessment and experimental task) all together were reasons to leave out eye-movement recordings. The relatively small size of the separate groups was reason to combine them.

CONCLUSIONS

This study clearly shows age- and task-specific differences in goal-directed aiming between children with INS and children with normal vision. The lower speed and harmonicity of the movements generated by children with INS alongside their homing-in problems as reflected by a larger endpoint scatter, specifically for small-amplitude movements, suggest these behavioral differences should be attributed to a perception-action based association between INS and the efficiency of goal-directed aiming movements rather than to visual impairment as such. The educational or clinical implication of the analyses presented here is that rehabilitation of children with INS should focus on the interaction between perception and action, which preferably should be initiated at a young age.

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